Nonuniform C-Band Loop Antenna

A New Approach for Future UWB Applications

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Abstract—**Antenna design becomes very difficult at very small wavelengths and a special lab is required to manufacture a small antenna which costs a lot. A new approach is proposed to enhance the bandwidth of the loop antenna which can be designed at very high frequency using conventional PCB design technique. The proposed antenna is a nonuniform loop and covers UWB frequency range. The nonuniform structure of the loop is designed using the concept of both thin and thick loop antenna together which leads to an improvement in the antenna bandwidth. The proposed nonuniform loop antenna covers a band of 91.4% which is higher than any existing printed loop antenna. The frequency ranges from 3.54GHz to 9.5GHz and the measured result is in agreement with the simulated result. This technique can be very helpful in designing UWB antennas in the range of Ku band or higher than this.**

Keywords-coplanar stripline; thin loop antenna; thick loop antenna; wire antenna; ultra wide band; nonuniform loop antenna

I. INTRODUCTION

UWB is a need of present and future communication systems as demand for more data is increasing. High-speed data transfer requires the availability of a larger band. In order to fulfill the need of larger bandwidth, broadband antennas are used as transmitting and/or receiving elements. Other UWB applications include location tracking and ground penetrating radars. So far monopole antennas appeared as strong candidates to fulfill the requirements of UWB applications. In order to improve gain and other electrical and radiation characteristics, metamaterials or EBG structures were added to monopole antennas. Dipole printed antennas fed with coplanar stripline (CPS) cover bandwidth from 3.1GHz to 11.4GHz. This structure has too many dimensional parameters in the antenna design [1]. A closed loop structure provides larger scope for the researchers to contribute. A square printed loop with L shape portion to its arm offers excellent performance at the lower-band of UWB system, ranging from 3.1GHz to 5.1GHz [2]. The antenna exhibits a -10dB return loss bandwidth over the entire frequency band. It is found that the lower band depends on the L portion of the loop antenna however the upper frequency limit is decided by the taper transmission line. The percentage of the bandwidth of the antenna is 48.78%. A printed loop antenna fed with coplanar waveguide can produce bandwidth of 1GHz and 1.14GHz. This antenna is suitable for applications in PCS and IMT 2000 systems. The antenna has high gain with omnidirectional radiation pattern [3]. A small size loop antenna fed with CPW line produces a 70% bandwidth. The small size of the antenna makes it useful for array applications [4]. A single loop antenna has a narrow circular polarized bandwidth. When this antenna is added with another loop antenna as a passive element, then a second band is created and the combination of the antennas produces a larger bandwidth with circular polarization [5]. The band enhancement technique [2] was extended to a circular loop and bandwidth of 88.6% was achieved. The proposed work failed to give any justification on the enhancement of bandwidth and the impact of proposed shape on the antenna radiation pattern was not considered.

II. PROPOSED NONUNIFORM LOOP ANTENNA

A circular loop antenna with a thickness factor larger than 9, is called a thin loop antenna, otherwise it is called a thick loop antenna. The thin loop has multiple resonating frequencies and larger resistance with fluctuating characteristic. On the contrary, a thick loop antenna is capacitive in nature with low and uniform resistance [6]. The thickness factor is defined in (1), where Ω is the thickness factor, r is the radius of the loop in m and b is the wire radius in m:

$$\Omega = 2\ln\left({}^{2\pi r}/_{b}\right) \tag{1}$$

A loop antenna is basically a narrow band antenna. The bandwidth of the antenna can be improved when both thin and thick loop antennas are added together to have a uniform standing wave ratio (SWR) [7]. Its loop is comprised of a thick loop with 8.8 thickness factor and a thin loop with 11.7 thickness factor and covers 88.6% bandwidth. A wire loop antenna can be modified into a printed loop antenna using (2) as given in [8]. The thickness factor can be calculated using (1) and (2), where w is the width of the printed loop and b is the wire radius:

$$b = w/4 \tag{2}$$

In order to further improve the loop antenna bandwidth, a new geometry is proposed and is shown in Figure 1. The proposed geometry has a gradual increase in the width of the loop to have thin and thick loop properties together, unlike the geometry in [7], which also has a step change in the width of the loop.

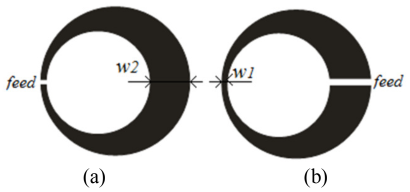


Fig. 1. Nonuniform loop with (a) feed at narrow width W1 (b) feed at wide width W2.

A loop antenna falls under two categories: 1) A large loop whose circumference is equal to or larger than a wavelength at a chosen frequency, 2) a small loop with circumference smaller than $\lambda/10$. A large loop is a good radiator while a small loop is a good receiver [9]. In order to cover the least frequency of 2GHz, the approximate radius of the loop using (3) and (4) is 24mm and the width of the loop is 1mm. Ω of the loop is 12.76 so it is thin in nature. The same antenna for 12mm width has Ω of 7.26 and is, a thick loop.

$$C = 2\pi r = \lambda \quad (3)$$

$$\lambda = c/f \quad (4)$$

where C is the circumference of the loop, r is the radius of the loop in m, λ is the wavelength in m, f is the frequency in Hz and $c$is the speed of light in m/s in free space. The antenna is simulated using CST STUDIO. The substrate used is FR-4 with a height of 0.8mm.

III. FEED LOCATION AND WIDTH IMPACT ON THE PERFORMANCE OF THE PROPOSED ANTENNA

The proposed geometry has minimum width W1 and maximum width W2 to give a nonuniform dimension. The outer radius of the loop is taken as 24mm. In order to analyze the characteristics of the nonuniform loop and the effect of this geometry on feed location, a feed is applied at one width and the same or other width of the loop varies.

A. Feed Impact at Narrow Width W1 with Varying Width W2

The possible advantage of the proposed structure is that there can be infinite locations for antenna excitation. This is because at different locations the feed will experience different loop width. Therefore the loop electrical properties will be different for different locations of the excitation due to its nonuniform structure. Nonuniform loop with thin width W1 of 1mm and thick width W2 of different values ranging from 6mm to 12mm is simulated. The feed to the loop is placed at the thin end W1. The result of the proposed nonuniform loop is compared with 1) a thin loop of 23.5mm radius with 1mm width having Ω=12.76 and 2) a thick loop of 18mm radius with 12mm width having a thickness factor of 7.26. In order to have the same loop size, i.e. thin loop, thick loop and nonuniform loop, the outer radius is kept 24mm. Since the proposed nonuniform loop has W1=1mm and width W2 varying from 6mm to 12mm, it is a combination of thin and thick loop. A thin loop of thickness factor of 12.76 shows a huge variation in resistance value. It ranges from 80Ω to more than 400Ω as is observed in Figure 2(a). The thin loop resonates at about 1.9GHz as shown in Figure 2(b). The thick loop of 7.26 thickness factor, as observed in Figure 2(b), has stable resistance and resonates at 6GHz.

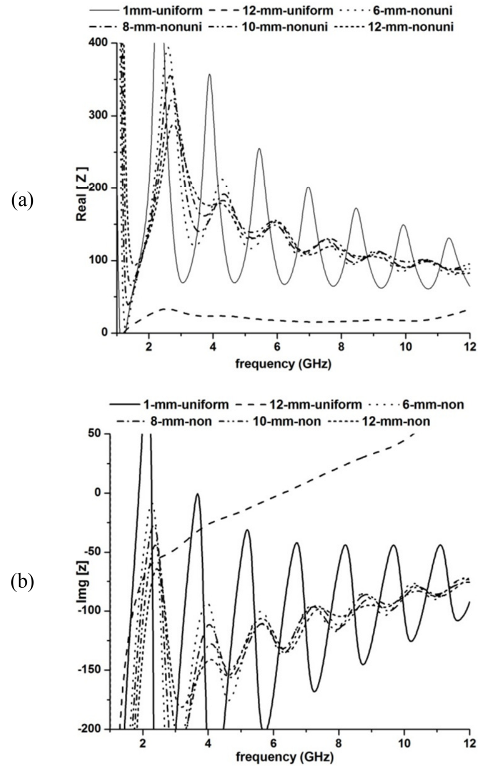
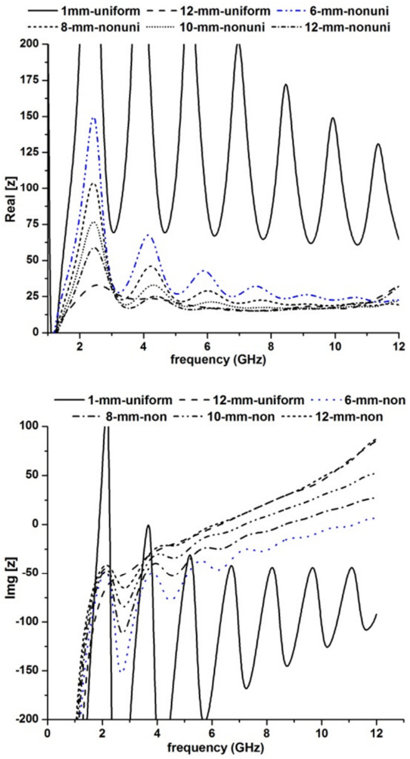


Fig. 2. Comparison of impedances of uniform and nonuniform loop when feed is applied at narrow width W1 and varying width W2.

It can be observed in Figure 2(a) that the resistance variation of the proposed loop antenna is reduced to a greater extent but it is larger than the resistance of the thick loop for all simulated cases. Similarly, the reactance of the nonuniform loop shows less variation when compared to the reactance of the thin antenna but it is larger than the reactance of the thick loop antenna as shown in Figure 2(b).

B. Feed Impact at Wide width W2 with Varying Width W2

In order to analyze the effect of feed locations on the characteristic of the nonuniform loop antenna, the feed is placed at wide end W2 as shown in Figure 1(b). The width W2 varies from 6mm to 12mm, while W1 is kept constant to 1mm. The behavior of the impedance of the nonuniform loop is shown in Figures 3(a) and 3(b). It is observed that the resistance of the nonuniform loop approaches the resistance of the thick loop antenna of uniform width of 12mm with Ω=7.26. The resistance varies between 24Ω to 75Ω from 3GHz onwards. In Figure 3(b), it can be observed that as W2 increases from 6mm to 12mm, the reactance of the nonuniform loop decreases and approaches the reactance of the thick loop (Ω=7.26) of 12mm width. The reactance of the nonuniform loop ranges from -75Ω to +50Ω for frequencies from 3.4GHz and onwards. The impedance of the proposed nonuniform loop under this case is smaller than in the previous case. The overall impedance of the proposed loop for all cases is much smaller than the impedance of the thin loop with thickness factor of 12.76. Any increase in W2 of the nonuniform loop reduces thickness factor of the antenna and antenna impedance approaches the impedance of thick loop with thickness factor 7.26.



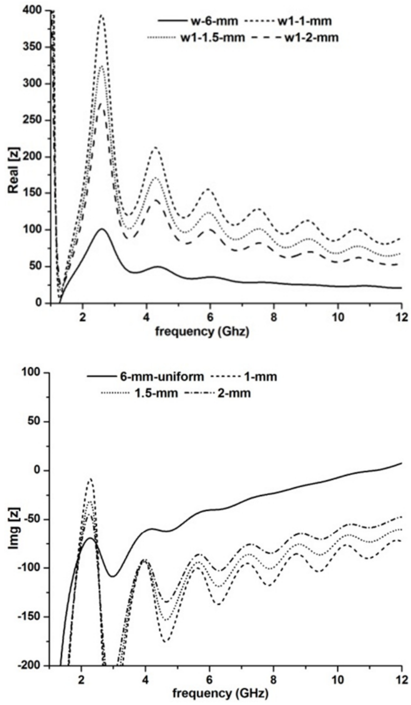
(a)

(b)

Fig. 3. Comparison of the reactance of uniform and nonuniform loop when feed is applied at wide width W2.

C. Feed Impact at Narrow Width W1 with Varying Width W1

Now the feed is placed at W1 and width W2 is kept at 6mm. W1 varies from 1mm to 2mm. The result of this nonuniform loop is compared with the uniform loop of 24mm outer radius with 6mm width. The outer radius of the nonuniform loop is kept at 24mm in order to keep the same maximum dimension of uniform and nonuniform loop. The uniform antenna of 6mm width with an outer radius of 24mm has uniform resistance less than 50Ω from 3.3GHz and onwards as shown in Figure 4(a). The nonuniform loop with W2 of 6mm and varying width W1 from 1mm to 2mm shows that antenna resistance decreases with increase in W1. Any increase in W1 leads to uniformity in the structure of the loop and also causes a drop in the thickness factor of the proposed antenna. Therefore the resistance of the nonuniform loop antenna decreases as shown in Figure 4(a). The antenna with uniform width of 6mm resonates at 11GHz. It is capacitive from 1GHz to 11GHz and then switches to inductive reactance. On the other hand, the reactance of the nonuniform loop is larger and capacitive from 1GHz to 12GHz and above. As W1 increases from 1mm to 2mm, the antenna reactance reduces for obvious reasons as shown in Figure 4(b).



(a)

(b)

Fig. 4. (a) Resistance and (b) Reactance comparison of uniform and nonuniform loop when feed is applied at varying narrow width W1.

D. Feed Impact at Wide Width W2 with Varying Width W1

Now the feed is located at wide width W2 and the width W1 varies from 1mm to 2mm. W2 is kept constant to 6mm. When the feed is shifted to W2 end, there is a huge difference observed in the reactance of the nonuniform loop antenna. In the uniform antenna, the shift in feed location does not influence the characteristics of the antenna as the dimension seen by the two terminal sources triggering the antenna is uniform. This is not the case with the nonuniform loop for the same two terminal sources. The nonuniform loop with thin dimension W1 of 1mm shows larger resistance. There is a continuous decrease in the resistance with increase in W1 as this leads to uniformity of the proposed structure. The variation in resistance is shown in Figure 5(a). Larger resistance is observed from 2GHz to 2.6GHz for W1 variation from 1mm to 1.5mm. The variation in resistance for W1 of 2mm is very small and is well aligned with the resistance variation of the uniform loop of width 6mm from 2.7GHz onwards. It can be observed in Figure 5(b) that the reactances of uniform and nonuniform loop are well aligned from 3GHz and above. The two antennas, uniform and nonuniform, differ in their reactance from 2.45GHz to 3GHz. Table I summarizes the impedance behavior of the loop with different W2 of 8mm and 10mm along with the earlier case of width W2 of 6mm. Width W1 ranges from 1mm to 2mm for all three cases. It can be concluded that for a feed at W1 antenna impedance decreases significantly as W2 increases. A huge fall in antenna impedance is observed when the loop is fed at W2. Therefore antenna impedance is a strong function of the feed location. Furthermore, the antenna impedance can be varied by changing W1 and W2. This property of the proposed loop is not available in any other loop antenna available in the literature.

(a)

(b)

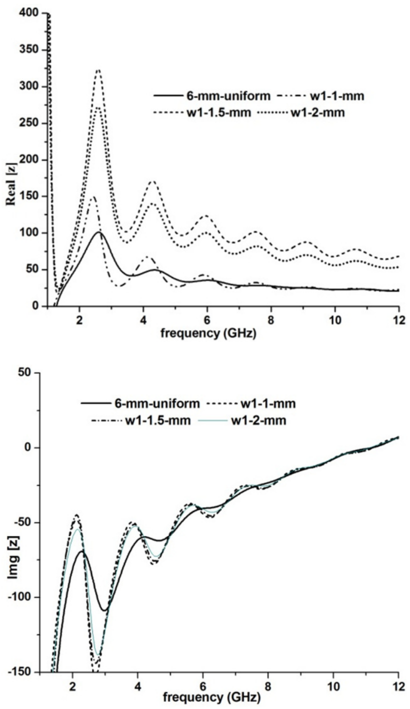


Fig. 5. (a) Resistance and (b) reactance comparison of uniform and nonuniform loop when feed is applied at wide width W2.

TABLE I. BEHAVIOUR OF PROPOSED NONUNIFORM LOOP ANTENNA

W2 (mm)	W1 (mm)	R/X (Ω) (4GHZ to 5GHz)		R/X (Ω) (8GHZ to 9GHz)		R/X (Ω) (11GHZ to 12GHz)	
		Feed at W1	Feed at W2	Feed at W1	Feed at W2	Feed at W1	Feed at W2
6	1	219/-134	49/-77	102/-87	23/-18	87/-77	21.3/4
	1.5	170/-124	52/-75	77/-80	24/-19	64/-66	21.6/3
	2	140/-113	52/-72	62/-69	23/-19	52/-54	21.7/3.4
8	1	183/-148	41/-51	97/-93	19/-105	87/-79	19/25
	1.5	146/-134	41/-49	76/-82	19/-1.7	66/-65	18/25
	2	122/-122	40.5/-47	63/-72	19/-1.5	53/-52	18/25
10	1	178/-144	31/-34	102/-100	17/13	88/-76	19/48
	1.5	140/-132	31/-33	80/-88	17/13	63/-64	19/47
	2	117/-120	30/-32	65/-74	16/13.8	51/-52	19/46

R-Resistance, X-Reactance

IV. LOCATING FEED FOR OPTIMUM BANDWIDTH

From the analysis above, it is concluded that antenna impedance is a function of the feed location. This section is dedicated to finding a suitable location of the feed to have the maximum bandwidth. The feed is applied from W1 end at 0^0 and is shifted to W2 end at 180^0 as shown in Figure 6(a). The reflection coefficient for all cases is compared in order to find the optimum feed location. Since the loop is a balanced antenna, it cannot be excited directly with SMA connector or coaxial cable. In order to excite the proposed loop with the help of SMA connector or any other unbalanced line, a coplanar strip line (CPS) is added to the loop as shown in Figure 6(b). For the simulations the outer radius of the nonuniform loop is kept at 24mm, the inner radius is 17.75mm with W1 of 2mm and W2 of 12mm. The inclusion of the CPS line converts the unbalanced field distribution from the SMA feed connector to a balanced field distribution at the loop [10]. The CPS feed line is placed at different locations and the results are compared in Figure 7. The detailed dimension of the CPS line is included in Figure 6(b).

(a)

(b)

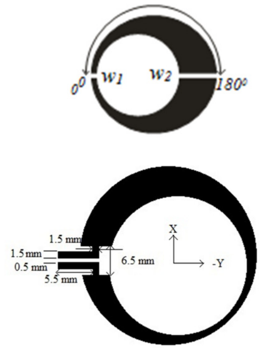


Fig. 6. The proposed nonuniform (a) showing various feed locations from W1 to W2 (b) loop with CPS feed line.

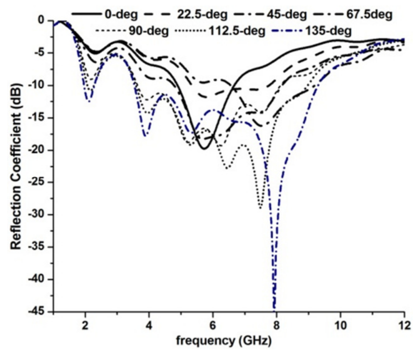


Fig. 7. Comparison of the reflection coefficient of the nonuniform loop for different feed locations.

It can be observed that the shift in the location of the feed influences the bandwidth of the antenna since the antenna impedance changes due to the change in the location of the feed as observed above. Table II summarizes the performance of the proposed loop in terms of % bandwidth of the loop with respect to different feed locations. It can be observed that the antenna gives the highest bandwidth when the feed is applied at 135^0. The available bandwidth is 91.4%. The band has lower cut off frequency of 3.54GHz and higher cut-off frequency of 9.5GHz. Table III compares the proposed nonuniform loop antenna with other existing loop antennas. It can be observed that the proposed loop has the highest electrical and radiation bandwidth. Figure 8 shows the radiation patterns in the range of 3.54GHz to 9.5GHz. The loop antenna is placed in X-Y plane as shown in Figure 6(b). The radiation pattern is of end fire type and is available along -Y axis, opposite to the feed of the loop antenna. It was observed that the pattern is always available opposite to the feed of the loop for all cases listed in Table II. It is important to note here that when the proposed loop is compared with the loop proposed in [7], there is very little improvement in the antenna bandwidth. The advantages of the proposed loop over the earlier are summarized in Table IV. The earlier loop requires BALUN transformer but the loop presented in this paper does not require it, so it occupies a smaller area on PCB. In addition, the size of the presented loop is almost half the size of the earlier loop whose outer dimension was 45mm. There are only three distinct locations for feed in the earlier loop: a) on the wide arm of the loop, b) on the thin arm of the loop, and c) between the interface of wide and thin arm of the loop. The loop in this paper has theoretically infinite locations to feed the antenna.

TABLE II. LOOP PERFORMANCE COMPARISON FOR DIFFERENT FEED LOCATIONS USING CPS.

Sr. No.	Feed Locations	f1-f2	% Bandwidth
1	0^0	4.9-6.7	31
2	22.5^0	5.4-7.6	34
3	45^0	6.5-9.2	34
4	67.5^0	4.8-8	50
5	90^0	3.58-6.7	60.7
6	112.5^0	3.7- 8.8	81.6
7	135^0	3.54-9.5	91.4

f1, f2- lower and upper cut off frequency

TABLE III. PROPOSED AND OTHER LOOP ANTENNAS COMPARISON

Sr. No.	%Bandwidth	Reference	Year
1	88.6	[7]	2016
2	67	[11]	2015
3	40.7	[12]	2012
4	70	[4]	2010
5	48.8	[2]	2005
6	91.4	Proposed	-------

TABLE IV. PROPOSED LOOP AND EARLIER LOOP COMPARISON

	Property			
	Size	% Bandwidth	Feed Locations	Radiation Pattern
Proposed Loop	Smaller	91.4	Infinite	Stationary
Earlier Loop	Larger	88.6	Three	Not available

V. MEASUREMENTS AND DISCUSSION

Figure 9 shows a photograph of the proposed antenna. The proposed nonuniform loop is excited with a SMA connector directly. Figure 10 shows the measured and simulated reflection coefficient for the loop with CPS line feed at 135^0. The measured result is in good agreement with the simulated one and ensures 91.4% bandwidth. The outer dimension of the loop is 24mm i.e. the antenna diameter is 48mm. The significant observation is that the loop antenna with outer dimension of 24mm and thickness factor of 12.76 resonates at around 1.9GHz. It resonates at about 6GHz when thickness factor changes to 7.26 as discussed earlier. The proposed loop is a combination of thin and thick loop with resonant frequency falling between 1.9GHz and 6GHz. The lowest cutoff frequency of the proposed loop is nearly 3.54GHz for which the antenna dimension should be smaller than 48mm. Therefore this technique can be useful for designing very high frequency antennas such as Ka band and higher where the dimension of the antenna becomes too small and a special lab is required for the manufacturing of the antenna.

VI. CONCLUSIONS

The proposed nonuniform loop antenna has the unique property of having infinite possibilities to feed the antenna. The antenna offers different electrical properties for different feed locations. This property is not available in the conventional structure of loop antenna.

(a)
(b)
(c)
(d)
(e)

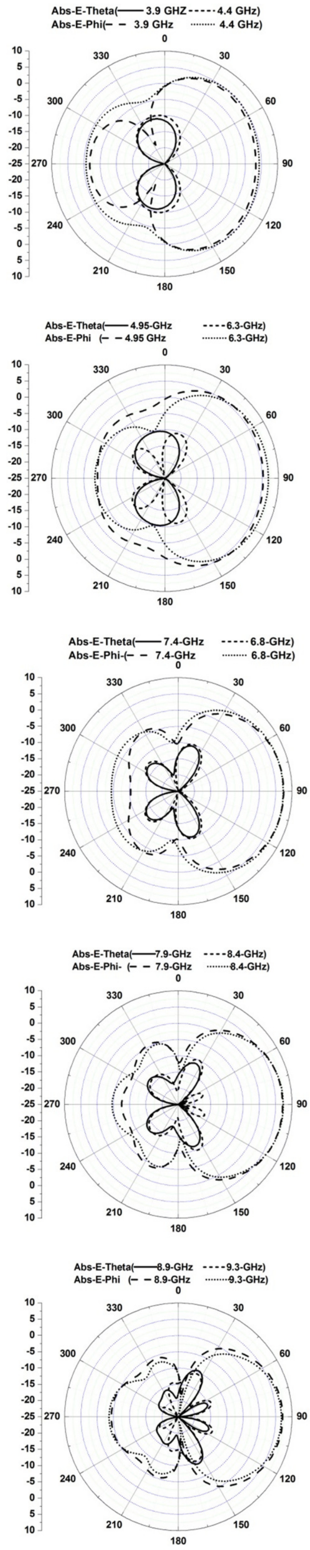


Fig. 8. Radiation pattern of the nonuniform loop at different frequencies.

The proposed structure with the CPS feed line can be excited with a coaxial SMA connector. The combination of thin and thick loop offers a wide bandwidth of 91.4%. The proposed dimension of the loop is expected to cover the lowest frequency of 2GHz but the lowest frequency obtained is 3.54GHz. This leads to an increase in the antenna dimension.

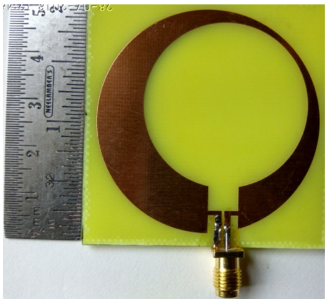


Fig. 9. Photograph of the proposed nonuniform loop antenna.

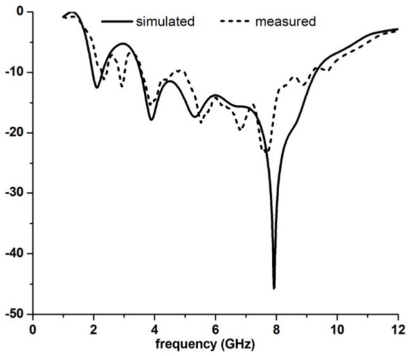


Fig. 10. The measured and the simulated reflection coefficient of the nonuniform loop antenna.

This approach can be used to design an antenna for Ka band applications or higher than Ka band where the antenna size becomes so small that a special lab is required to manufacture it. If this technique is used to design antennas at such a high frequency, the dimension of the loop will be sufficiently larger and simple pcb design technique can be used to manufacture the antenna at low cost. The proposed antenna shows wider % bandwidth than any other printed wideband loop antenna. The simulated and measured bandwidth of the loop is 91.4% with unidirectional radiation pattern oriented opposite to the feed. Since the pattern is available in the opposite side of the feed, the proposed antenna can have multiple feed points and pattern reconfigurability can be achieved.

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